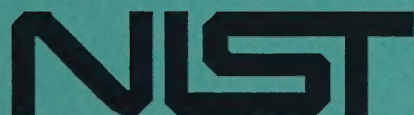


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**ADVANCED TECHNOLOGY PROGRAM
CASE STUDY: Early Stage Impacts of the Printed Wiring
Board Research Joint Venture, Assessed at Project End**

Albert N. Link, Ph.D.
Consulting Economist



**UNITED STATES DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology**

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Prepared for:

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National Institute of Standards and Technology
Advanced Technology Program
Gaithersburg, MD 20899

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Executive Summary

This report summarizes the technical accomplishments and presents selected measures of research efficiencies and early stage economic impacts of the Printed Wiring Board (PWB) Research Joint Venture Project. The project was cost-shared by the Advanced Technology Program (ATP), a unique partnership in which the Federal government and private industry jointly fund research and development projects that have high technical risk and commensurate large potential for creating broad-based economic benefits for the United States. It was carried out by a group of seven companies, with participation by Sandia National Laboratories. The period covered by the study is from mid-1991 through mid-1996, the time during which the research was conducted.

The ATP has an evaluation program to assess how well the funded projects meet technological milestones, to determine their short-run impacts and, ultimately, their long-run impacts, and to improve the program's effectiveness. Most of the 352 projects the ATP has funded, from its start-up in 1990 through 1997, were funded only in the last several years, and it is premature to attempt to measure empirically the long-term impacts of the program. However, some of the earlier projects are now beginning to reach completion of their research phases, and it is possible to conduct at least preliminary assessment of their technical accomplishments, their early impacts on the companies involved, and, to a much lesser extent, the early impacts on the rest of the economy.

This study addresses a five-year joint venture funded in the 1990 competition, ATP's first. The PWB Research Joint Venture Project was first addressed in an interim evaluation study in April 1993, which focused on early gains in research efficiencies in the project and early gains in productivity improvements by project participants up to that time. This report updates the 1993 study by documenting the technical accomplishments of the PWB Research Joint Venture Project through completion of the ATP funding period in 1996, and by offering selected quantitative and qualitative measures of research cost savings and early stage economic impacts realized by the end of that same period.

Over the decade prior to the ATP PWB Project, the U.S. PWB industry had experienced sharp declines in the number of companies in the industry and in their world market share. The outlook for the future was not considered favorable unless substantial advances could be made in terms of producing more dimensionally stable laminates, lower cost and higher performance materials, increased wiring densities, and more efficient and environmentally friendly processes. Most of the companies in the industry lacked the capacity to carry out research; only a few of the more than 700 companies remaining in 1991 were able to undertake advanced research. Yet a whole set of new capabilities were needed if the U.S. PWB industry was to remain viable in the future. Printed wiring boards are important because they are the backbone of the electronics industry. A group of companies in the industry saw the ATP as a possible mechanism for overcoming the high risk and large cost of attempting a turn-around, and organized the PWB joint venture to apply in ATP's first competition, the 1990 General Competition. It received one of the 11 research awards that year out of a field of 249 project applicants. The project was begun in 1991.

The major findings of the study are as follows:

- The ATP provided \$12.866 million over the five-year research project, and industry provided \$13.693 million, for a combined research effort of \$26.559 million. After the project started, the U.S. Department of Energy added \$5.2 million for Sandia National Laboratories' participation in the research joint venture, which reportedly would not have been provided without the ATP initiative. Hence, the overall research effort was \$31.759 million, taking into account funding by the member companies, ATP, and Sandia National Laboratories. This represented a substantial expansion in the amount of advanced research in the area of printed wiring boards.
- The PWB Research Joint Venture Project accomplished all of the originally proposed goals, and the project exceeded the original expectations of the members. The joint venture entailed 62 distinct research tasks carried out by the project's four research teams. Technical accomplishments included, among other things, the following:
 1. the "Materials Team" developed the technology for making single-ply laminates and a new, dimensionally stable thin film material that has superior properties to any other material used by the industry,
 2. the "Surface Finishes Team" improved test methods that determine the effectiveness of various materials during the soldering process,
 3. the "Imaging Team" developed and successfully demonstrated the process required to obtain a yield of greater than 98 percent for 3 mil line and space features, and
 4. the "Product Team" (also a research team) developed a revolutionary new interconnect structure and demonstrated its feasibility in production.
- Based on a survey of the PWB Research Joint Venture member companies, the joint venture would not have occurred without ATP funding because, even for the group, the risk and associated financial cost of the project would have been too great.
- According to survey results, of the 62 research tasks completed by the PWB Joint Venture, about one-half would not have been undertaken at all in the absence of ATP funding, and the remaining one-half would have been delayed by at least one year in an industry where timing is critical.
- According to the survey results, the companies estimated that without the ATP Research Joint Venture, the approximately 32 research tasks that they thought they would have eventually done on their own—but with a delay—would have cost them an additional \$35.5 million to complete at the same technical level and in the same time frame as achieved by the PWB Research Joint Venture, that is, a total of \$67.259 million. The \$35.5 million savings in research efficiencies accruing to the member companies on these tasks consisted of:

1. \$24.7 million in workyears saved by performing the research in collaboration,
 2. \$3.3 million in testing material and machine time savings by sharing test data and equipment, and
 3. \$7.5 million in other research cost savings.
- In addition to the above research cost savings from collaborating on the 32 research areas the member companies would otherwise have done independently, the companies obtained these new technical capabilities sooner than they otherwise would have.
 - More significantly, from the other 32 research tasks that they would not have done at all without the ATP Research Joint Venture, the member companies obtained a whole set of additional new technical capabilities that they otherwise would not have had.
 - At the end of the project, member companies estimated that partial implementation of new processes resulting from about 40 percent of the 62 research areas, that they had undertaken in “spin-off” fashion, was already yielding directly traceable productivity gains in the production of printed wiring boards. Some examples of the production-productivity gains that had been realized by member companies by the end of the project were:
 1. reduced ply count in PWBs without the previous attendant problems—one company reported savings of \$3 million or more per year for this advance,
 2. reduced costly scrap loss by the use of a model to predict inner layer shrinkage—one company reported savings of \$1.4 million or more per year due to a dramatic cut in scrap due to this advance, and
 3. reduced solder defects—one company reported a 50 percent decrease in solder joint defects, which were numbering more than 1,000 per board, due to this advance.
 - The PWB industry as a whole is rapidly obtaining many of the benefits of the new methods and techniques developed by the PWB Research Joint Venture through an active transfer of scientific information about the new production processes to other producers outside the joint venture, as well as to universities, as evidenced by the following:
 1. 214 research papers had been presented by PWB members by the end of the project,
 2. two research papers received Best Paper Awards at conferences,
 3. numerous research papers have been cited in other academic manuscripts, and

4. independent PWB shops were beginning to invest their own funds to incorporate the new processes developed by the joint venture (a finding based at this time on anecdotal information).
- PWB manufacturers inside and outside of the PWB Research Joint Venture expressed interest in forming additional collaborative research efforts.
 - Members of the PWB Research Joint Venture indicated that as a result of the project their companies had become more competitive in certain segments of the world market – including the computer sector, the fastest growing segment of the industry. Furthermore, they indicated that the domestic PWB industry as a whole had improved its competitive position in selected world markets as a result of the accomplishments of the project.
 - At a recent meeting, the National Center for Manufacturing Sciences (NCMS) gave its collaborative project excellence award to the ATP-sponsored PWB project, and the NCMS president credited the project with saving the PWB industry in the U.S. with its approximately 200,000 jobs.
 - With the passage of additional time, it is anticipated by the member companies that productivity gains from implementation of the 62 research tasks addressed by the PWB Research Joint Venture will grow exponentially as more of the new process technologies are put into practice by the members, and as the new knowledge and techniques are widely disseminated across the PWB industry.

In addition to strengthening the competitiveness of U.S. producers and increasing their share in world markets, aggregate long-term benefits of the PWB Research Joint Venture Project will come through the incorporation of lower-cost and improved printed wiring boards in the myriad of electronics products, which will provide great benefit to consumers.

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ADVANCED TECHNOLOGY PROGRAM

Early State Impacts of the Printed Wiring Board Joint Venture, Assessed at Project End¹

I. Background Information

A. The Advanced Technology Program (ATP)

The goals of the Advanced Technology Program (ATP), as stated in its enabling legislation, the Omnibus Trade and Competitiveness Act of 1988 (P.L. 100-418),² and modified by the American Technology Preeminence Act of 1991 (P.L. 102-245), are to assist U.S. businesses in creating and applying the generic technology and research results necessary to:

- (1) *commercialize significant new scientific discoveries and technologies rapidly; and*
- (2) *refine manufacturing technologies.*

These goals were also restated in the *Federal Register* on July 24, 1990:

The ATP . . . will assist U.S. businesses to improve their competitive position and promote U.S. economic growth by accelerating the development of a variety of pre-competitive generic technologies by means of grants and cooperative agreements.

The ATP received its first appropriation in FY 1990. The program funds research, not product development. Most of the joint-venture projects last from three to five years. Nascent commercialization of the technology resulting from the project might overlap the research effort, but the full translation of the technology into products and processes generally takes a number of years. The ATP has an evaluation program to assess project and program impacts.³ Although full economic impacts of most ATP funded research will not likely be realized for some time, ATP's evaluation plan is to assess both short- and long-term effects.

¹ In April 1993, two years after the five-year printed wiring board joint venture was funded, a summary of the early-stage effects was prepared (Link 1993). This updated report considers the cumulative economic impacts identifiable with the joint venture up to the time of its completion.

² This section of the Omnibus Trade and Competitiveness Act of 1988 is also known as the Technology Competitiveness Act.

³ See Ruegg (1996).

B. The ATP Award to the Printed Wiring Board Research Joint Venture

In April 1991, ATP announced that one of its initial eleven awards was to a joint venture led by the National Center for Manufacturing Sciences (NCMS). The objective of the project was to research aspects of printed wiring board (PWB) interconnect systems.⁴ The ATP project description follows:

Printed wiring boards (PWBs) are often overlooked in discussions of microchips and other advanced electronic components, but they form the backbone of virtually every electronic product, providing connections between individual electronic devices. Although to date PWB technology has kept pace with the increased speed and complexity of microelectronics, it is approaching fundamental limits in materials and processes that must be overcome if the U.S. industry is to maintain a competitive position. (The U.S. share of the \$25 billion world market dropped from 42 to 29 percent in 3 years.) Four members of the NCMS consortium, AT&T, Texas Instruments, the Digital Equipment Corporation, and Hamilton Standard Interconnect, Inc., will work with the Sandia National Laboratories (U.S. Dept. of Energy) to develop a more consistent epoxy glass material with improved mechanical characteristics for PWBs, improved processes and process-control techniques to produce more reliable solder connections, improved methods and technologies for fine-line imaging on the boards, and a better technical understanding of the chemistry underlying key copper-plating processes. Nine hundred U.S. firms in the PWB industry could benefit.

<i>Project length:</i>	<i>5 years</i>
<i>ATP funds:</i>	<i>\$13,783K</i>
<i>Cost-shared funds (est.)</i>	<i>\$14,674K</i>
<i>Total project funds (est.)</i>	<i>\$28,457K</i>

The project was completed in April 1996. Actual ATP costs (pre-audited) amounted to \$12.866 million over the five-year (statutory limit) funding period. Actual industry costs amounted to \$13.693 million. During the project the U.S. Department of Energy added an additional \$5.2 million. Thus, total project costs were \$31.759 million.⁵

⁴ The National Center for Manufacturing Sciences (NCMS) is the Nation's largest not-for-profit collaborative research consortium. In cooperation with government and industry, NCMS is working to meet the challenges posed by global competition to the American manufacturing community. NCMS served as project administrator.

⁵ These end-of-project cost figures were provided by ATP.

II. Overview of the Printed Wiring Board Industry

A. Early History of the Industry⁶

Dr. Paul Eisler, an Austrian scientist, is given credit for developing the first printed wiring board. After World War II, he was working in England on a concept to replace radio tube wiring with something less bulky. What he developed is similar in concept to a single-sided printed wiring board.

A printed wiring board (PWB) or printed circuit board (PCB) is a device that provides electrical interconnections and a surface for mounting electrical components. While the term PWB is more technically correct because the board is not a circuit, the term PCB is more frequently used in the popular literature.⁷

Based on Eisler's early work, single-sided boards were commercialized during the 1950s and 1960s, primarily in the United States. As the term suggests, a single-sided board has a conductive pattern on only one side. During the 1960s and 1970s, the technology was developed for plating copper on the walls of drilled holes in circuit boards. This advancement allowed manufacturers to produce double-sided boards with top and bottom circuitry interconnections through the holes. From the mid-1970s through the 1980s there was tremendous growth in the industry. In the same period, PWBs became more complex and dense, and multilayered boards were developed and commercialized. Today, about 66 percent of the domestic market is multilayered boards.⁸

⁶ This section draws from Flatt (1992).

⁷ Definitionally, a PWB consists of a conductive pattern on a common surface to provide point-to-point connection of discrete components, but not to contain printed components. A PCB is a conductive pattern composed of printed components, printed wiring, or a combination thereof, all formed in a predetermined design and attached to a common surface. See Institute for Interconnecting and Packaging Electronic Circuits, IPC (1995a).

⁸ Based on 1994 data, multilayered boards accounted for \$3.92 billion of the \$5.96 billion rigid PWB market (IPC 1995a).

B. Trends in the Competitiveness of the PWB Industry

As shown in Table 1, the United States dominated the world PWB market in the early 1980s. However, Japan steadily gained market share from the United States. By 1985, the U.S. share of the world market was, for the first time, less than that of the rest of the world excluding Japan; and by 1987 Japan's world market share surpassed that of the United States and continued to grow until 1990. By 1994, the U.S. share of the world market was approximately equal to that of Japan, but considerably below the share of the rest of the world, which was nearly as large as the two combined. While there is no single event that explains the decline in U.S. market share, one very important factor, at least according to a member of the PWB Project team, has been "budget cut backs for R&D by OEMs because owners demanded higher short-term profits," which led to deterioration of the industry's technology base.⁹

In 1991, the Council on Competitiveness issued a report on American technological leadership.¹⁰ Motivated by evidence that technology has been the driving force for economic growth throughout American history, the report documented that as a result of intense international competition, America's technological leadership had eroded. In the report, U.S. technologies were characterized in one of four ways:

Strong: meaning that U.S. industry is in a leading world position and is not in danger of losing that lead over the next five years.

Competitive: meaning that U.S. industry is leading, but this position is not likely to be sustained over the next five years.

Weak: meaning that U.S. industry is behind or likely to fall behind over the next five years.

Losing Badly or Lost: meaning that U.S. industry is no longer a factor or is unlikely to have a presence in the world market over the next five years.

The 1991 Council on Competitiveness report characterized the U.S. PWB industry as "Losing Badly or Lost." However, in 1994, the Council updated its report and upgraded its assessment of the domestic industry to "Weak" due in large part to renewed R&D efforts by the industry.¹¹

⁹ Original equipment manufacturers (OEMs) are manufacturers that produce PWBs for their own end-product use.

¹⁰ See Council on Competitiveness (1991).

¹¹ See Council on Competitiveness (1996).

Table 1**World Market Share for Printed Wiring Boards**

Year	U.S.	Japan	Others
1980	41%	20%	39%
1981	40%	22%	38%
1982	39%	23%	38%
1983	40%	21%	39%
1984	42%	24%	34%
1985	36%	25%	39%
1986	34%	32%	34%
1987	29%	30%	41%
1988	28%	27%	45%
1989	28%	31%	41%
1990	26%	35%	39%
1991	27%	34%	39%
1992	29%	31%	40%
1993	26%	28%	46%
1994	26%	26%	48%

Note: Percentages are rounded; they are based on the value of sales.

Source: IPC (1995a, 1995b) as referenced in the 1995 National Technology Roadmap for Electronic Interconnections.

C. Current State of the PWB Industry

Table 2 shows the value of U.S. PWB production from 1980 through 1994. While losing ground in relative terms in the world market, the PWB industry grew in absolute terms over these 15 years. In 1994, production in the domestic market was \$6.43 billion, nearly 2.5 times the 1980 level, without adjusting for inflation; in real dollars, that equates to 1.5 times the 1980 level.

There are two types of PWBs that account for the value of U.S. production shown in Table 2: rigid and flexible. Rigid PWBs are reinforced. For most panels, this reinforcement is woven glass. Rigid PWBs can be as thin as 2 millimeters (mils) or as thick as 500 mils. Generally, rigid boards are used in subassemblies that contain heavy components. Flexible PWBs do not have any woven glass reinforcement. This allows them to be flexible. These boards are normally made from thin film materials around 1 to 2 mils thick, typically from polyimide. As shown in Table 3, rigid boards account for the lion's share of the U.S. PWB market. In 1994, nearly 93 percent of the value of U.S. PWB production was attributable to rigid boards. Of that, approximately 66 percent was multilayer boards.¹²

As shown in Table 4, Japan dominated the flexible PWB world market in 1994; but North America, the United States in particular, about equaled Japan in the rigid PWB market.

There are eight distinct market segments for PWBs:¹³

Automotive: engine and drive performance, convenience and safety, entertainment, and other applications for diagnostic display and security.

Business/Retail: copy machines, word processors, cash registers, POS terminals, teaching machines, business calculators, gas pumps, and taxi meters.

Communications: mobile radio, touch tone, portable communication, pagers, data transmissions, microwave relay, telecommunications and telephone switching equipment, and navigation instruments.

Consumer Electronics: watches, clocks, portable calculators, musical instruments, electronic games, large appliances, microwave ovens, pinball/arcade games, TV/home entertainment, video records, smoke, and intrusion detection systems.

Computer: mainframe computers, mini-computers, broad level processors, add-on memories, input devices, output devices, terminals, and printers.

Government and Military/Aerospace: radar, guidance and control systems, communication and navigation, electronic warfare, ground support instrumentation, sonar ordinance, missiles, and satellite related systems.

Industrial Electronics: machine and process control, production test measurement material handling, machining equipment, pollution, energy and safety equipment, numerical control power controllers, sensors, and weighing equipment.

¹² Multilayer boards consist of alternating layers of conductor and insulating material bonded together. In comparison, single-sided boards have a conductive pattern on one side, while double-sided boards have conducting patterns on both. See Microelectronics and Computer Technology Corporation and IPC (1995).

¹³ These definitions come from IPC (1992). In years prior to 1994, there was a single category of computer and business equipment.

Instrumentation: test and measurement equipment, medical instruments, and medical testers, analytical nuclear, lasers, scientific instruments, and implant devices.

As shown in Table 5, the computer sector absorbs the greatest proportion of U.S.-produced rigid and flexible PWBs. Comparing rigid and flexible board usage, the communications sector uses a higher proportion of rigid boards and a lower proportion of flexible boards, while the military uses a higher proportion of flexible boards relative to its use of rigid boards.

PWB producers are divided into two general groups: manufacturers that produce PWBs for their own end-product use and manufacturers that produce boards for sale to others. Those in the first group are referred to as original equipment manufacturers (OEMs) or captives, and those in the second group are referred to as independents or merchants. As shown in Table 6, independents accounted for an increasing share of all PWBs in the United States.¹⁴ Their share of the total domestic market for rigid and flexible PWBs increased from 40 percent in 1979 to 83 percent in 1994. For rigid PWBs, independents accounted for 93 percent of the market in 1994.¹⁵

Table 7 shows PWB sales for 1990 and 1995 of the ten major OEMs in 1990. IBM's sales decreased during this period, but it sold its military division during the period. AT&T's sales increased, but in 1996 the PWB producing division of AT&T became Lucent Technologies. Lucent Technologies is now an independent producer. Digital's PWB segment became independent Amp-Akso in 1995, so 1995 sales for Digital are noted as na, or not applicable. Amp-Akso, as an independent producer, had sales in 1995 of \$105 million. Hewlett-Packard and Unisys were no longer in the industry in 1995 and hence their 1995 sales are noted as \$0. During this period, the major OEMs experienced the continuing market effects associated with their strategic decision to cut back or eliminate R&D in PWBs.

In comparison to the information in Table 7 on OEMs, Table 8 shows that the major independents' sales have generally increased. As a whole, their sales increased at a double-digit annual rate of growth over the time period 1990 to 1995. The major independent shops do not conduct R&D, but they continued to enjoy increasing sales of their technologically simpler PWBs.

¹⁴ According to NCMS sources, the profits on PWBs are small. As OEMs/captives continually re-evaluated the strategic importance of maintaining the large R&D overhead burden associated with their PWB production process, they opted to decrease production in favor of purchasing PWBs from independents.

¹⁵ See IPC (1995a).

Independent manufacturers of PWBs, for the most part, are relatively small producers, as shown in Table 9.¹⁶ In both 1991 and in 1994, the vast majority of independent producers had less than \$5 million in sales. The number of small independents appears to be declining sharply. Whereas 33 companies had sales greater than \$20 million in 1991 (with 16 of those having sales greater than \$40 million), 50 companies had sales above \$20 million in 1994 (with 18 of those having sales over \$50 million and 5 of the 18 having sales over \$100 million). On the other hand, the number of companies with less than \$5 million in sales fell to about 600 in 1991, around 450 in 1994, and the declining trend is continuing.

Table 2

Value of U.S. Production of Printed Wiring Boards
(\$ millions, nominal)

Year	Value
1980	\$2,603
1981	\$2,816
1982	\$2,924
1983	\$4,060
1984	\$4,943
1985	\$4,080
1986	\$4,033
1987	\$5,127
1988	\$5,941
1989	\$5,738
1990	\$5,432
1991	\$5,125
1992	\$5,302
1993	\$5,457
1994	\$6,425

Source: IPC (1992, 1995a).

¹⁶ Similar information is not available for OEMs.

Table 3

Value of U.S. Production of Printed Wiring Boards, by Market Type

Type	1991	1994	1999 est.
Rigid	\$4.76 bil.	\$5.96 bil.	\$8.06 bil.
Flexible	\$370 mil.	\$470 mil.	\$678 mil.

Source: IPC (1992, 1995a) and Business Communications Company (1994).

Table 4

World Production of Printed Wiring Boards, by Board Type: 1994

Region	Rigid	Flexible
Japan	27%	48%
Taiwan	6%	--
China/Hong Kong	6%	--
Rest of Asia	9%	6%
Germany	5%	--
Rest of Europe	13%	--
Europe	--	14%
Africa/Mid-East	4%	--
N. America	29%	30%
S. America	1%	--
Rest of World	--	2%
TOTAL	100%	100%
	\$21.2 bil.	\$1.65 bil.

Source: IPC (1995b).

Table 5

U.S. Production by Market Type and Market Segment: 1994

Segment	Rigid	Flexible
Automotive	12%	12%
Business/Retail	3%	0%
Communications	25%	11%
Consumer Electronics	4%	3%
Computer	35%	45%
Government and Military	7%	20%
Industrial Electronics	6%	4%
Instrumentation	9%	4%
TOTAL	\$5.96 bil.	\$470 mil.

Source: IPC (1995b).

Table 6

Producers of Printed Wiring Boards, by Producer Type

Type	1979	1981	1991	1994
Independents	40%	47%	66%	83%
OEMs	60%	53%	34%	17%

Source: IPC (1992) and Flatt (1992).

Table 7

Ten Major OEMs in North America in 1990: PWB Sales in 1990 and 1995
(\$ millions, nominal)

Company	1990	1995
IBM	\$418	\$300
AT&T	\$195	\$300
GM Hughes/Delco	\$153	\$140
Digital (DEC)	\$125	<i>na</i>
Hewlett-Packard	\$68	\$0
Unisys	\$55	\$0
Texas Instruments	\$50	\$50
Raytheon	\$35	\$35
Rockwell	\$24	\$24
Thompson	\$24	\$24

Note: *na* denotes not applicable. Digital's PWB producing group became independent Amp-Akso in 1995. Amp-Akso PWB sales in 1995 were \$105 million.

Source: Flatt (1992) and personal correspondence with Kirk-Miller Associates.

Table 8

Ten Major Independents in North America in 1990: Sales in 1990 and 1995
(\$ millions, nominal)

Company	1990	1995
Hadco	\$158	\$258
Photocircuits	\$125	\$265
Diceon Electronics	\$113	<i>na</i>
Zycon	\$108	\$170
Circo Craft	\$84	\$135
Advance Circuits	\$83	\$153
Tyco	\$66	<i>na</i>
Tektronix	\$61	<i>na</i>
Sanmina	\$61	<i>na</i>
Continental Circuits	\$60	\$110

Note: *na* denotes not applicable. In 1995, these companies were either no longer in the market or no longer among the top ten producers.

Source: Flatt (1992) and Miller (1995).

Table 9

Number of Independent Manufacturers of Printed Wiring Boards by Sales

Sales	1991	1994
Over \$20 mil.	33	50
\$10 - \$20 mil.	40	70
\$5 to \$10 mil.	60	100
Under \$5 mil.	592	450+
TOTAL	725	670+

Source: IPC (1992, 1995a).

III. Printed Wiring Board Research Joint Venture

A. Roles and Relationships among Members of the Joint Venture

Although Digital Equipment (DEC) was one of the companies involved in the original NCMS proposal to ATP, it participated in the project for only 18 months. Its decision to withdraw was, according to NCMS, due strictly to financial conditions at the corporation at that time. DEC's financial condition did not improve-- ultimately leading to the closing and sale of its PWB facilities.

Three companies joined the joint venture to assume DEC's research responsibilities: AlliedSignal in 1993, and Hughes Electronics and IBM in 1994. Also, Sandia National Laboratories became involved in the joint venture during 1992, as anticipated when NCMS submitted its proposal to ATP for funding. Sandia subsequently obtained an additional \$5.2 million from the Department of Energy to support the research effort of the joint venture. These membership changes are summarized in Table 10.

The PWB research joint venture can be described in economic terminology as a horizontal collaborative research arrangement. Economic theory and empirical studies suggest that research efficiencies will be realized when horizontally related companies form a joint venture, due to the reduction of duplicative research and the sharing of research results.¹⁷ This conclusion is supported in the case study here, as evidenced by the quantitative estimates of cost savings reported by the members, and by the specific case examples cited in support of the cost-savings estimates.

Characteristics of the joint venture member companies are summarized in Table 11. AT&T, Hughes, IBM, and Texas Instruments were four of the leading domestic captive producers of PWBs when the project began; they were also members of NCMS, the joint venture administrator. Although in the same broadly-defined industry (i.e., they are horizontally related), two of these companies, AT&T and IBM, were not direct competitors in PWBs because their PWBs were produced for internal use in different applications. AT&T produced PWBs primarily for telecommunications applications while IBM's application areas ranged from laptop to mainframe computers. Although Hughes and Texas Instruments produced for different niche markets, they did compete with each other in some Department of Defense areas. Hamilton Standard, no longer a producer, purchases boards to use in its production of engines and flight control electronics. AT&T and Texas Instruments are not involved in these latter two product areas. In contrast to all of the other companies, AlliedSignal is a major supplier of materials (e.g., glass cloth, laminates, resins, copper foil) to the PWB industry. In addition, it is a small-scale captive producer of multilayered PWBs.

¹⁷ See Link and Bauer (1989).

Table 10

Membership Changes in the PWB Research Joint Venture

Original Members, April 1991	1992	1993	1994	April 1996
AT&T	AT&T	AT&T	AT&T	AT&T
Digital Equipment	--	--	--	--
Hamilton Standard	Hamilton Standard	Hamilton Standard	Hamilton Standard	Hamilton Standard
Texas Instruments	Texas Instruments	Texas Instruments	Texas Instruments	Texas Instruments
--	--	AlliedSignal	AlliedSignal	AlliedSignal
--	Sandia	Sandia	Sandia	Sandia
--	--	--	Hughes Electronics	Hughes Electronics
--	--	--	IBM	IBM

Note: Funding under the ATP award to the PWB research joint venture commenced in April 1991. The ATP funding period ended in April 1996.

B. Organizational Structure of the Joint Venture

A Steering Committee, with a senior technical representative from each of the participating organizations worked collectively to direct and control the four research teams to ensure that each was meeting the technical goals of the project. NCMS provided the program management, coordination, facilitation, and interface with ATP for the PWB project. NCMS coordinated and scheduled activities and provided the interface between the administrative functions of accounting, contracts, and legal functions related to intellectual property agreements.

Table 11

Characteristics of Members of the Joint Venture

Member Company	Type of Producer	Primary Market Niche
AT&T	Captive	telecommunications
Hamilton Standard	n.p.	aerospace
Texas Instruments	Captive	computers
AlliedSignal	Captive	defense
Sandia	n.p.	n.p.
Hughes Electronics	Captive	Computers
IBM	Captive	Computers

Note: *n.p.* denotes not a producer of PWBs.

The joint venture was organized to “mimic a company with a chain of command,” according to one member of the Steering Committee. According to this member:

If it was not organized this way then no one would be accountable. Most of the people had this project built into their performance review. If they failed on the project then they failed at work. The structure also allowed ease of reporting. The information flowed up to the team leader as the focal point for information distribution. The team leader would then report to the Steering Committee of senior managers who were paying the bills.

The joint venture’s research activities were divided into four components:

- Materials
- Surface Finishes
- Imaging
- Product (research; not product development)

Prior to proposing to ATP's 1990 General Competition, the members of the research joint venture conducted a systems analysis of the PWB manufacturing process and concluded that fundamental generic technology development was needed in these four components of the PWB business.

Each component consisted of a combination of research areas which:

- provided significant improvements to existing processes
- explored new technology to develop break-through advances in process capabilities.

A multi-company team of researchers was assigned to each of the four research components. The four research teams were involved in 62 separate tasks.

Each team had specific research goals as noted in the following team descriptions.

Materials Team: The majority of PWBs used today is made of epoxy glass combinations. The goal of the Materials Team was to develop a more consistent epoxy glass material with improved properties. The team was also to develop non-reinforced materials that exceeded the performance of epoxy materials at lower costs. Better performance included improved mechanical, thermal, and electronic properties (e.g., higher frequency) to meet improved electrical performance standards.

Surface Finishes Team: Soldering defects that occur during assembly require repair. The goal of the Surface Finishes Team was to develop test methods to use during fabrication to determine the effectiveness of various materials used during the soldering process and to develop alternative surface finishes. These test methods can be applied during fabrication to ensure the PWB meets assembly quality requirements.

Imaging Team: The goal of the Imaging Team was to investigate and extend the limits of the imaging process to improve conductor yield, resolution, and dimensional uniformity.

"Product" Team: Originally, this team was known as the chemical processing team. Its goal was to investigate the feasibility of additive copper plating and adhesion of copper to polymer layers. Based on input from the industry which revealed that this was not the best research path to take, its focus changed as did its name. The revised goal of the Product Team, after studying roadmaps and specification predictions, was to develop high density interconnect structures. (The "Product" Team, like the other teams, carried out research.)

Given the generic research agenda of the joint venture at the beginning of the project, the organizational structure seemed conceptually appropriate for the successful completion of all research activities. At the close of the project, this continued to be the opinion of the members. As a member of the Steering Committee noted:

There is better synergy when a management team directs the research rather than one company taking the lead. Members of the Steering Committee vote on membership changes, capital expenditures, licensing issues, patent disclosures and the like. As a result of this type of involvement, there are high-level champions in all member companies rather than in only one.

C. Technical Accomplishments¹⁸

NCMS released a summary statement of the technical progress of the joint venture at the conclusion of the project. The PWB Research Joint Venture Project accomplished all of the originally proposed research goals and the project exceeded the original expectations of the members. Based on the NCMS summary and extensive telephone interviews with each team leader, the following major technical accomplishments at the end of the project have been identified.¹⁹ The accomplishments are also summarized in Table 12.

Materials Team: The major technical accomplishments of the Materials Team were the following:

- (1) Developed single-ply laminates that have resulted in cost savings to industry and in a change to military specifications that will now allow single-ply laminates.²⁰
- (2) Developed a new, dimensionally stable thin film material that has superior properties to any other material used in the industry. This outcome has resulted in a spin-off NCMS project to continue the development of this material with the goal of commercialization by 1998.
- (3) Identified multiple failure sources for “measling”.²¹ The findings revealed that PWBs were being rejected, but that the real source for the board’s failure was not being correctly identified as a problem with the adhesion of resin to the glass.

¹⁸ These technical accomplishments were compiled with the assistance of Ron Evans, then of NCMS.

¹⁹ As discussed in the following section, economic impact data were collected regarding these technical accomplishments.

²⁰ Single ply laminates is one of the best of the technical accomplishments that are already being implemented; it is generating cost savings in the industry, and especially for those companies that supply to the military. Many other technical achievements, such as the Magnified Image Projection Printing Tool (see Imaging Team below), are still in the process of full implementation and could have even greater impacts.

²¹ Measling is the separation or delamination at the glass resin interface in a PWB. This separation results in a void that can allow moisture to be trapped in the board, causing a short circuit. Detection of measling can result in the board being rejected. If not detected, the board will eventually fail to operate (e.g., the board will short circuit).

- (4) Completed an industry survey that led to the development of a Quality Function Deployment (QFD) model (discussed below). The model defines the specifications of the PWB technology which are considered most important to customers.
- (5) Completed an evaluation (and compiled a database) of over 100 high performance laminates and other selected materials that offer significant potential for improving dimensional stability and plated through-hole (PTH) reliability. Revolutionary materials exhibiting unique properties, and potentially eliminating the need for reinforced constructions, have been identified.
- (6) Developed a predictive mathematical model that allows the user to predict dimensional stability movement of various construction alternatives.²²
- (7) Developed the finite element analysis model (FEM), with the Product Team, that predicts PTH reliability.
- (8) Developed a low profile copper foil adhesion on laminate process such that military specifications could be revised to allow for lower adhesion of copper.²³
- (9) Developed a plasma monitoring tool.²⁴
- (10) Filed a patent disclosure for a Block Co-polymer replacement for brown/black/red oxide treatments for inner layer adhesion. This substitute will facilitate lower copper profiles and thinner materials.

Surface Finishes Team: The major technical accomplishments of the Surface Finishes Team were the following:

- (1) Improved test methods that determine the effectiveness of various materials during the soldering process, producing the conclusion that one surface finish (imidazole) is applicable to multiple soldering applications.
- (2) Commercialized the imidazole surface finish through licensing the technology to Lea Ronal Chemical Company.
- (3) Conducted a survey of assembly shops to determine parameters that manufacturers monitor in order to make reliable solder interconnections.
- (4) Evaluated numerous other surface finish alternatives, and presented the data at the spring 1995 IPC Expo in San Jose; the paper won the Best Paper Award at the conference.
- (5) Filed three patent disclosures: A Solderability Test Using Capillary Flow, Solderability Enhancement of Copper through Chemical Etching, and A Chemical Coating on Copper Substrates with Solder Mask Applications.
- (6) Facilitated the adoption of test vehicles developed by the team for development use, thus saving duplication of effort.²⁵

²² Multilayered boards move during fabrication. This model predicts that movement thereby ensuring that the components on each layer will be in alignment.

²³ The development of low profile copper adhesion will generate cost savings to the industry because less material is needed in production, especially for those companies producing under military contract.

²⁴ This tool is used for end point detection and has already been transferred to industry by Sandia acting through SEMATECH. A patent disclosure has been filed.

²⁵ A test vehicle is a device that is designed and manufactured to test new technology by simulating or emulating a product or family of products. NCMS reported that these test vehicles are also used outside of the research joint venture on other NCMS research projects.

Imaging Team: The major technical accomplishments of the Imaging Team were the following:

- (1) Developed and successfully demonstrated the process required to obtain greater than 98 percent yields for 3 mil line and space features. (At project start, the industry benchmark was 30 percent yield.) The team also obtained over 50 percent yield for 2 mil line and space features. (At project start, the industry benchmark yield was below 10 percent.)
- (2) Developed and put into use test equipment and data processing software to evaluate fine-line conductor patterns for defect density, resolution limits, and dimensional uniformity.²⁶
- (3) Applied for a patent on conductor analysis technology and licensed the technology to a start-up company-- Conductor Analysis Technologies, Inc. (CAT), in Albuquerque, NM. CAT now sells this evaluation service to the PWB industry. According to NCMS, it is highly unlikely that a private sector firm would have developed this technology outside of the joint venture. Thus, commercializing this technology through CAT, Inc. has benefited the entire industry.²⁷
- (4) Evaluated new photoresist materials and processing equipment from industry providers, and designed new test patterns for the quantitative evaluation of resists and associated imaging processes.
- (5) Developed and proved feasibility of a new photolithography tool named Magnified Image Projection Printing; this tool has the potential to provide a non-contact method of printing very fine features at high yields and thus has generated enough interest to form a spin-off non-ATP funded NCMS project to develop a full scale alpha tool. No results are yet available.

Product Team: The major technical accomplishments of the Product Team were the following:

- (1) Developed a revolutionary new interconnect structure called Multilayer Organic Interconnect Technology (MOIT), described as the next generation Surface Laminar Circuit (SLC) technology; and demonstrated the feasibility of MOIT on 1,000 input/output Ball Grid Array packages and test vehicles using mixed technologies, including flip-chip.²⁸
- (2) Completed an industry survey related to subtractive chemical processes, additive processes, and adhesion. The results of the survey showed that there was not industry interest in the research area; as a consequence, a different research path was taken (with ATP's approval).²⁹
- (3) Identified chemical properties to enhance understanding of the adhesion of copper to base material, and magnetic-ion plating of metal conductive layers; also developed plated through-hole models and software that are highly efficient and cost effective to run.

²⁶ The test methodology also provides statistical process control data. Objective tests are necessary to ensure that new imaging techniques are suitable for production use.

²⁷ See Rhodes (1996) for a description of this start-up company.

²⁸ IBM is continuing research on MOIT on its own.

²⁹ As previously noted, this team was originally called the chemical processing team.

- (4) Developed evolutionary test vehicles that simulate Personal Computer Micro Interface Card Adapter (PCMICA) and computer workstation products. These test vehicles have been used to pull the development of new materials, surface finishes, and imaging technology by other teams.
- (5) Performed several small hole drilling studies and minimum plating requirement studies for PTHs.
- (6) Delivered a paper on the finite element analysis model (FEM), developed with the Materials Team, which won the Best Paper Award at the fall 1994 IPC meetings in Boston.

Table 12

Summary of Major Technical Accomplishments, by Team

Materials Team	Surface Finishes	Imaging Team	Product Team
(1) single ply laminates	(1) imidazole	(1) 2 and 3 mil line and space demonstration	(1) MOIT
(2) thin film	(2) database	(2) conductor patent	(2) industry survey
(3) failure analysis	(3) filed patent disclosures	(3) test patterns	(3) copper adhesion properties
(4) QFD model	(4) test vehicles	(4) photolithography tool feasibility	(4) test vehicles
(5) materials evaluation			(5) small hole drilling studies
(6) predictive model			
(7) FEM			
(8) copper foil adhesion			
(9) plasma monitoring tool			
(10) Block-Co-polymer			

Note: A more complete description of these technical accomplishments is in the text of the report.

QFD = Quality Function Development model.

FEM = Finite Element Analysis model.

MOIT = Multilayer Organic Interconnect Technology

IV. Research Cost Savings, Early Productivity Gains, and Other Effects

A. Conceptual Approach to the Analysis

The conceptual approach to the assessment of early economic gains from this joint venture parallels the approach used by others in economic assessments of federally-supported R&D projects.³⁰ Specifically, a hypothetical counter-factual survey experiment was conducted. Participants in the joint venture were asked to quantify a number of related metrics that compared the current end-of-project technological state to the technological state that would have existed at this time in the absence of ATP's financial support of the joint venture. Additional questions were also posed to each team leader in an effort to obtain insights about the results of the joint venture affecting the industry as a whole.

In the 1993 study (Link, 1993), it was determined that only 6.5 of the 29 then on-going tasks would have been started in the absence of the ATP award. At project end, there were 62 research tasks, and it was estimated that about half of these would not have been started in the absence of ATP funding.³¹ Accordingly, a counter-factual survey was created to examine that subset of tasks that would have been started even in the absence of ATP support. Each of the project team leaders was briefed about this study at the April 1996, end-of-project Steering Committee meeting. It was decided that the survey would focus on only one limited dimension of economic impact-- namely cost savings attributable to formation of the joint venture, in terms of only those projects that the member companies would have pursued individually anyway in the absence of the ATP supported joint venture. This limited focus has both positive and negative aspects. On the positive side, it ensured participation in the economic analysis by all members of the joint venture. And, estimates of quantified impacts would represent a lower bound estimate of actual economic value of the joint venture. On the negative side, a number of technical accomplishments that would not have come about but for the joint venture have the potential in time to generate large economic benefits to the PWB industry and to consumers of PWB-based products. No aggregate estimate of the potential value of these impacts was attempted in this study due to its early nature, though examples of productivity impacts currently realized by several of the companies were documented. Looking at developments several years downstream should shed more light on diffusion of the technology developed in the project and their benefits in use.

³⁰ See Link (1996b).

³¹ The number of research areas increased from 29 to 62; as the companies worked together, new problems were identified and tasks were identified to solve them.

B. Methodology for Data Collection

The methodology used to collect information for this study was defined, in large part, by the members of the joint venture. In particular, members requested that the information collected first be screened by NCMS to ensure anonymity and confidentiality, and then only be provided for the study in aggregate form. Under this condition, all members of the PWB research joint venture were willing to participate in the study by completing a limited survey instrument and returning it directly to NCMS.

The survey instrument considered these related categories of direct impact:³²

- Scale, Scope, and Coordination Efficiencies: Estimated Workyears Saved by Carrying Out the Research as a Joint Venture
- Testing Materials and Machine Time Savings
- Other Research Cost Savings
- Cycle-Time Efficiencies: Shortened Time to Put into Practice New Procedures and Processes
- Productivity Increase in Production.

The survey also considered these two broad categories of indirect impact:

- Technology Transfer to Firms Outside the Joint Venture
- International Competitiveness Issues

Focused survey findings were supplemented with selected open-ended comments offered by respondents; by personal discussions with team leaders and company representatives during the April 1996, Steering Committee meeting; and by follow-up telephone and electronic mail discussions with available members.

³² Impact data were requested from each member by project, although it was understood that only aggregate totals would be made available for this study. In practice, however, because of the integrated nature of the research, companies generally reported the total research cost saving from the joint venture's activities to NCMS.

C. Survey Results: Two Snapshots in Time, 1993 and 1996

All members concurred that the joint venture would not have formed by them or by others in industry in the absence of ATP funds to leverage the overall research program. Each member of the PWB research joint venture was asked which research tasks in which they were involved would have been started by their company in the absence of the ATP-funded joint venture. Aggregate responses suggested that only one-half of the tasks would have begun in the absence of ATP funding. The other one-half would not have been started either because of the cost of such research or because of the related risk. Tasks that would not have been started without ATP funding include:

- development of alternative surface finishes
- projection imaging evaluations
- revolutionary test vehicle designs
- plasma process monitoring equipment
- PTH modeling software, and also
- approximately 25 others.

Of those tasks that would have been started without ATP funding, the majority would have been delayed by at least one year for financial reasons.³³

1. Direct Impact on Member Companies

Regarding the five categories of direct impacts:

a. Scale, Scope, and Coordination Efficiencies: Estimated Workyears Saved By Carrying Out the Research as a Joint Venture

Two years into the project, the members estimated a total of 79 workyears had been saved from avoiding redundant research, valued at more than \$10 million.³⁴ At the end of the project, the members estimated a total of 156 workyears had been saved. The total value of these workyears saved was estimated at \$24.7 million.³⁵ The estimated \$24.7 million in savings was based on an estimate of additional labor costs member companies would have incurred if research tasks that they have been willing to conduct individually in the absence of the ATP joint venture were in fact actually carried out individually and without collaboration.³⁶

³³ This information comes from qualitative responses; specific time periods were not obtained individually for each of the 62 research tasks. As one member of the Steering Committee noted about this one year time savings: "Time to market is everything. Process knowledge became available one year sooner. The PWB industry recovery occurred one year sooner and is still growing."

³⁴ Reported in Link (1993).

³⁵ In general, companies estimated the value of workyears saved by imputing their standard 1995 rates. According to NCMS, these rates ranged from \$107,000 to \$200,000 per workyear, including an average burden rate of 100 percent.

³⁶ See Link, Teece, and Finan (1996) for related examples of like labor savings that result from joint venture research.

An example of workyears saved by avoiding redundant research was provided by a member of the Steering Committee:

The universal test vehicle developed by the imaging team was the foundation for the co-development and sharing of research results. Two examples of this relate to the evaluation of etchers and the evaluation of photoresists. Regarding etchers, one of the member companies did the initial evaluation, Sandia did the validation, and other member companies implemented the findings. Similarly, individual companies evaluated selected photoresists and then shared their results with the others. All members benefited from this joint development and sharing by avoiding redundant research time and expenses.

b. Testing Materials and Machine Time Savings

Two years into the project, the members estimated cost savings to be over \$2 million from saving in research testing materials and research machine time. At the end of the project, the members estimated the total value of savings in research testing materials and machine time to be over \$3.3 million.

Relating to research testing materials savings, a member of the Steering Committee noted:

Before the consortium, there was no central catalogue of all the base materials used to produce printed wiring boards. Now, the Materials Component of the PWB research joint venture has produced a complete database of PWB materials that includes data on composition, qualifications, properties, and processing information for the domestic rigid and microwave materials. The information in this catalogue has saved research testing materials and will make it easier for designers and fabricators to select materials without having to search through supplier literature.

This member went on to note:

Considerable problems were encountered in creating the database because (1) materials suppliers do not provide standardized property test data; (2) all of the data needed to process the material were not readily available; and (3) some of the test data appeared to be exaggerated. The database is presently available within the consortium and there are plans to make the database available to the entire industry over the Internet.³⁷

³⁷ No projection as to when this might occur was offered by members of the Steering Committee.

c. Other Research Cost Savings

In the 1993 study, members were asked a catch-all question relating to all other research cost savings associated with the research areas that would have been started in the absence of ATP funds, excluding labor and research testing material and machine time. In 1993, these other cost savings totaled \$1.5 million. In the 1996 survey, the same catch-all question was asked, and members' responses gave cost savings of over \$7.5 million.

Therefore, quantifiable research cost savings attributable to ATP funds and the formation of the joint venture were \$35.5 million, at the end of the project,—\$24.7 million in workyears saved, \$3.3 million in testing material and machine time saved, and \$7.5 million in other research cost savings. In other words, members of the joint venture reported that they would have spent collectively an additional \$35.5 million in research costs to complete the identified subset of research tasks that they would have conducted in the absence of the ATP-funded joint venture.

d. Cycle-Time Efficiencies: Shortened Time to Put into Practice new Procedures and Processes

Two years into the project, the members estimated that shortened time to put new procedures and processes into research practice was realized from about 30 percent of the tasks, and the average time saved per research task was nearly 13 months. At the end of the project, the members estimated that shortened time to practice was realized in about 80 percent of the research tasks that would have been started in the absence of ATP funds, and the average time saved per task was 11 months.³⁸ Members did not quantify the research cost savings or the potential revenue gains associated with shortened time to practice.

As an example of shortened time to put into practice new procedures and processes, a member of the Steering Committee noted:

The use of the AT&T image analysis tool and the improvements made in the tool during the contract has made a significant reduction in the evaluation time needed for photoresist process capability studies. This reduction has occurred due to the improved test methodology and the significant improvements in the speed and accuracy now available in making photoresist analysis.

³⁸ Members of the research teams were not asked to value research-related savings from shortened time to practice, based on advice from the members during the pre-testing phase of the survey. The pre-testing group based this advice on previous experience with scientists who, when asked to quantify such savings, would simply associate the total cost savings from a month saved in research time with the labor cost of an additional man-month of effort. Certainly, such an evaluation would result in an under estimate of the economic advantages of completing research sooner than would have otherwise been the case. Such related economic advantages include the non-labor research costs saved and the sooner-than-would-others-be-the-case increase in sales.

e. Productivity Increase in Production

Two years into the project, members of the Steering Committee estimated that participants in the project had realized productivity gains in production which could be attributed to research developments in about 20 percent of the 29 research areas. The then-to-date production cost savings totaled about \$1 million.

At the end of the project, the members estimated productivity gains in production which could be traced to research developments in about 40 percent of the 62 research areas.³⁹ The teams estimated the value of these productivity gains in production, to date, to be just over \$5 million. And, given that the PWB research joint venture's research has just completed, future productivity gains will, in the opinion of some team leaders, increase exponentially.⁴⁰

One example of productivity improvements in production relates to switching from two sheets of thin B-stage laminate to one sheet of thicker B-stage laminate. One member of the Steering Committee noted:

For a business like ours, the cost saving potential was enormous. The problem was that reducing the ply count in a board carried risk: drill wander, reliability, thickness control, dimensional stability, and supply. The consortium provided the resources to attack and solve each of these problems. The result was that we were able to quickly convert all production to thicker B-stage, saving at least \$3 million per year. Without the consortium this conversion might not have occurred at all.

A second example of productivity improvement relates to dimensional stability. In particular, another member of the Steering Committee noted:

The inability to accurately predict inner layer shrinkage leads to a serious compromise with interconnection density and often leads to costly scrap. At the beginning of this program, our facility was in the 8 to 10 mil range and mis-registration scrap costs were in the range of \$1.5 million per year. This problem was an area of special concern to the consortium members. As a result of this project, data exist that lead to an understanding of the problem, and a predictive model has been developed that is now being used to compensate for the art work associated with the circuit image on the boards. Our current capability is 5 to 6 mils and scrap is below \$100,000 per year. The work of the consortium made these improvements possible.

³⁹ It was not possible to segment productivity improvements attributable to the group of research projects that would have been undertaken absent ATP funding from those that would not have been undertaken, due to the complementary effects of research project results on production.

⁴⁰ Quantitative estimates of future productivity gains were not offered by the members.

A third member of the Steering Committee reported:

Our company has reduced solderability defects by 50 percent due to the efforts of the surface finishes team on the PWB interconnect program. The defect levels decreased from 4 to 2 defects per 1,000 solder joints due to reduced variation in tin alloy and contamination at the solder reflow process.⁴¹

And a fourth member commented:

The data collected from the NIST ATP program for improved registration and productivity gains were presented to the Defense Electronic Supply Center to convince them to allow single ply prepegs in construction of military PWBs. My company will obtain an on-going benefit from this due to a 30 percent reduction in materials cost and improved registration of the PWBs which will improve yield.

2. Indirect Impact on Member Companies and the PWB Industry

Two categories of indirect impact were identified which already are beginning to extend beyond the member companies to the entire industry: advanced scientific knowledge important to making PWBs, and improvements in international competitiveness. For these types of impact, descriptive information was collected to illustrate the breadth of the impact, but no effort was made to estimate aggregate dollar value or to segment them according to tasks that would or would not have been begun in the absence of ATP funding. This approach was based on advice of the Steering Committee which felt that attempting aggregate dollar valuations at this time would be extremely speculative in nature.

a. Technology Transfer to Firms Outside the Joint Venture

Two years into the project, the members estimated that 12 research papers had been presented to various industry groups; 40 professional conferences fundamental to the research of the joint venture had been attended; information from the research tasks was shared with about 30 percent of the industry supplying parts and materials to the PWB industry; and personal interactions had occurred between members of the Imaging Team and suppliers of resist materials to the industry.

At the end of the project, a total of 214 papers related to the research findings from the PWB project had been presented, 96 at professional conferences and 118 at informal gatherings of PWB suppliers and at other forums. Additional papers were scheduled for presentation at the time of this study.

⁴¹ There are more than 1,000 solder joints per PWB.

Members of the joint venture offered the opinion that such transfers of scientific information benefited the PWB industry as a whole by informing other producers of new production processes. They also benefited the university research community as evidenced by the fact that these papers are being cited in academic manuscripts.

Members of the Materials Team attended 10 conferences at which they interacted with a significant portion of the supplying industry. Specifically, they estimated that they interfaced regarding the PWB project with 100 percent of the glass/resin/copper suppliers, 100 percent of the flex laminators and microwave laminators, 90 percent of the rigid laminators, and 50 percent of the weavers.

Members of the Steering Committee were asked to comment on the usefulness, as of the end of the project, of these technology transfer efforts. While all thought that they were important to the industry, one member specifically commented:

One indication of the successfulness of the technology transfer efforts can be reflected in the fact that two of the PWB program papers presented at the IPC conferences were selected as best papers at these conferences. The IPC conferences are recognized worldwide as the premier PWB industry conferences. I think this shows that the industry appreciated the depth of the technology effort. Another indication of the usefulness of the technology transfer process is the fact that new PWB manufacturers are exhibiting interest in joining two proposed follow-on programs to continue certain areas of the current research.

Another member noted that his company relied on an independent PWB shop for dense boards. A measure of the success of the joint venture's technology transfer efforts is that this independent supplier, not a participant in the joint venture, has also increased its yield of these boards.

All members agreed that it was premature, even at the end of the project, to attempt to estimate in dollar terms the value to the industry of these knowledge spillover benefits.

b. International Competitiveness Issues

The health of the domestic PWB industry is fundamental to these companies becoming more competitive in the world market. At a recent meeting, NCMS gave its collaborative project excellence award to the ATP-sponsored PWB project. At that meeting the NCMS president credited the project with saving the PWB industry in the U.S. with its approximately 200,000 jobs.

As shown in Table 13, the members of the PWB Research Joint Venture perceived that as a result of their involvement in the joint venture, their companies have become more competitive in certain segments of the world market such as computing, the fastest growing market for PWBs. Although any one member company is involved in only one or two market segments, thus limiting the number of team members' responses relevant to each market segment, all members indicated that their companies' market share either stayed the same or increased as a result of being involved in the PWB project.

Likewise, as shown in Table 14, members perceived that the domestic PWB industry as a whole has increased its competitive position in selected world markets as a result of the accomplishments of the joint venture.

Most respondents expressed an opinion on how the PWB Research Joint Venture has affected the industry share in the different segments of the world PWB market. The responses indicate that the PWB project has increased industry's share in every market segment, with the strongest positive responses in the computer and military segments. No member was of the opinion that they or other members of the joint venture had increased their share at the expense of non-members, and this can be attributed to the fact that the results of the PWB project have been widely disseminated.

In addition, some members of the Steering Committee felt that the research results from the PWB Research Joint Venture had the potential to enhance the international competitive position of the U.S. semiconductor industry. It was the opinion of one member that:

Through this program, the PWB industry is learning to produce higher density PWBs with finer lines, reduced hole sizes, and new surface finishes. This is allowing the semiconductor industry to decrease the size of their component packages or eliminate them totally. This should have a pronounced effect on the competitiveness of the semiconductor industry in the future, although there is no evidence to date.

Table 13

Competitive Position of Member Companies in the World PWB Market

<i>As a result of my company's involvement in the PWB program, my company's share of each of the following segments of the PWB market has ...</i> <i>(increased=3; stayed the same=2; decreased=1; no opinion=0)</i>	
Market Segment	My Company's Market Share Has ...
Automotive	2.00 (n=1)
Communications	2.50 (n=4)
Consumer Electronics	2.00 (n=1)
Computer and Business Equipment	2.67 (n=3)
Government and Military	2.50 (n=4)
Industrial Electronics	2.33 (n=3)
Instrumentation	2.00 (n=3)
Note: n = number of respondents to the question. Their mean response is shown.	

Table 14

Competitive Position of PWB Industry in the World PWB Market

<i>I perceive that as a result of the accomplishments of the PWB program, the PWB industry's share of the following segments of the world PWB market has ...</i> <i>(increased=3; stayed the same=2; decreased=1; no opinion=0)</i>	
Market Segment	World Market Share Has ...
Automotive	2.20 (n=5)
Communications	2.67 (n=6)
Consumer Electronics	2.60 (n=5)
Computer and Business Equipment	2.83 (n=6)
Government and Military	3.00 (n=6)
Industrial Electronics	2.50 (n=6)
Instrumentation	2.33 (n=6)
Note: n = number of respondents to the question. Their mean response is shown.	

D. Summary and Interpretation of the Survey Results

ATPs funding of the PWB Research Joint Venture Project has thus far had a number of direct and indirect economic impacts. Of the direct impacts, the largest to date has been the increase in R&D efficiency. The project achieved at least a 53 percent reduction in overall research costs. The increase in research efficiency has in turn has led to reduced cycle times for both new project development and new process development. Collectively, the result has been in productivity improvements for member companies and improved competitive positions in the world market. As a result of knowledge dissemination activities by members of the joint venture, capabilities across the entire industry are expanding. These technology advancements are thus improving the competitive outlook and world market share of the U.S. PWB industry.

The survey findings associated with the above direct and indirect economic benefits are summarized in Table 15. Therein, the categories of direct economic impacts to member companies are separated into those for which dollar values were obtained and those for which dollar values were not obtained, so-called quantified and non-quantified economic impacts.

The survey results described in the previous sections and summarized in Table 15 should be interpreted as only partial and preliminary estimates of project impacts. First, although ATP funding of the joint venture has led directly to research cost savings and early production cost savings and quality improvements, the bulk of the production cost savings and performance gains will be realized in the future both in member companies and in other companies in the industry as the research results diffuse and are more widely implemented. As such, the valued economic impacts reported in Table 15 are a conservative lower-bound estimate of the long-run economic benefits associated with ATP's funding of the joint venture research.

In the methodology implemented thus far, data collection has focused on gathering from participants best estimates of cost savings and economic benefits, relative to a counter-factual situation without the ATP. The participants in the PWB Research Joint Venture are obviously those in the most informed position to discuss research cost savings, potential applications, and economic consequences that they have realized from the results obtained. The methodology does not as yet include consideration of market determined economic benefits deriving from the joint venture research. Full impacts across the marketplace cannot be observed instantaneously at the end of the project, but only in the future as research results diffuse and become embodied in PWB products.

Table 15

Summary of Survey Findings on Partial Early-Stage Economic Impacts

Categories of Partial Early-Stage Economic Impacts	After 2 Years	At End of Project
Direct Impacts to Member Companies		
Quantified Economic Impacts*		
Research Cost Savings		
Workyears saved	\$10.0 mil.	\$24.7 mil.
Testing materials and machine time saved	\$2.0 mil.	\$3.3 mil.
Other research cost savings	\$1.5 mil.	\$7.5 mil.
Production Cost Savings		
Productivity improvements	\$1.0 mil.	\$5.0 mil.
Non-Quantified Economic Impacts*		
Shortened Time to Practice		
Average time saved per research task	12.7 months	11.0 months
Indirect Impacts on Member Companies		
Competitive Position in World Markets	increased	increased
Spillover Impacts on PWB Industry		
Technology Transfer		
Research papers	12	214
Conferences attended	40	96
Competitive Position in World Markets	increased	increased

Note: * These impacts are based only on those research tasks that the members thought they would eventually have done without the ATP, and not the cost and time savings associated with the new capabilities resulting from those tasks that they would not have done at all without the ATP.

V. Concluding Observations

During the April 1996, Steering Committee meeting of the PWB Research Joint Venture, the members of the committee were asked to respond to the ten statements in Table 16 using the response categories of *strongly agree*=4, *agree*=3, *disagree*=2, *strongly disagree*=1, and *no opinion*=0. Beside each statement is the mean response; no member responded with no opinion.⁴²

As the response scores indicate, the Steering Committee overwhelmingly agreed about the impact of the PWB Research Joint Venture on commercialization, refinement of manufacturing technologies, and competitiveness. The strongest agreement came regarding the future impact of the PWB research joint venture on the industry (Statement 4 in Table 16).

Lastly, the members of the Steering Committee were asked to complete the following statement: *My company has benefited from its involvement in the PWB joint venture in such non-technical ways as...* Representative responses were:

- *We have learned to work and be much more open with other industry members. We have learned where other companies stand on technology. We have learned we in the industry all have the same problems and can work together to solve them. We have learned how to work with the Federal Labs, something we have never done before.*
- *We have an increased awareness of industry trends, needs, and approaches. We have learned that our company's intellectual property is not as proprietary as we initially believed—rarely can it be directly applied by our industry colleagues.*
- *We have gained prestige from being associated with the program. The joint NCMS/NIST/ATP research program has a national recognition. Suppliers that would not normally participate in collaborative projects will when a team like this is formed to become a joint customer.*

Lastly, the members were read the goals of the ATP as stated in its enabling legislation (and noted in Section I of this report). Albeit qualitative information, the members of the Steering Committee of this joint venture generally agreed that the ATP had indeed fulfilled its stated goals in the case of the PWB Research Joint Venture.

⁴² The representative from Sandia National Laboratories chose not to participate in this exercise.

Table 16

Importance of the PWB Research Joint Venture
(Response codes to the following statements are *strongly agree*=4;
agree=3; *disagree*=2; *strongly disagree*=1; *no opinion*=0)

Statement 1: The PWB joint venture helped <i>my company</i> commercialize new scientific discoveries and technologies more rapidly than would have occurred had my company not participated in the joint venture.	3.375
Statement 2: The PWB joint venture will help <i>my company</i> commercialize new scientific discoveries and technologies more rapidly than would have occurred had my company not participated in the joint venture.	3.375
Statement 3: The PWB joint venture helped the <i>PWB industry</i> in general commercialize new scientific discoveries and technologies more rapidly than would have occurred had the joint venture not been established	3.50
Statement 4: The PWB joint venture will help the <i>PWB industry</i> in general commercialize new scientific discoveries and technologies more rapidly than would have occurred had the joint venture not been established.	3.626
Statement 5: The PWB joint venture helped <i>my company</i> refine manufacturing technologies more rapidly than would have occurred had my company not participated in the joint venture.	3.50
Statement 6: The PWB joint venture will help <i>my company</i> refine manufacturing technologies more rapidly than would have occurred had my company not participated in the joint venture.	3.375
Statement 7: The PWB joint venture helped the <i>PWB industry</i> in general refine manufacturing technologies more rapidly than would have occurred had the joint venture not been established.	3.375
Statement 8: The PWB joint venture will help the <i>PWB industry</i> in general refine manufacturing technologies more rapidly than would have occurred had the joint venture not been established.	3.50
Statement 9: The PWB joint venture assisted <i>my company</i> improve their competitive position in the world market by accelerating the development of a variety of pre-competitive generic technologies.	3.125
Statement 10: The PWB joint venture assisted the <i>PWB industry</i> in general improve their competitive position in the world market by accelerating the development of a variety of pre-competitive generic technologies.	3.25

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APPENDIX 1: 1996 NCMS Survey Instrument

**NCMS/NIST PWB
Economic Impact Study**

Company Name

Est. Workyears Saved	Shortened Time to Practice	Productivity Improvement Increases	Testing Material and Machine Time Savings	Place an "X" if project would have started without this program	Money Saved
Yr.	Mo.	%	\$(K)	X	\$(K)

Materials Team

High Performance Laminate data base					
QFD Study Information					
CTE Modeling Software Tool					
Standardization and Consolidation Information					
Thermal defects and adhesion work					
AT&T TEK Track Exercise					
SNL Leap Frog Materials					
Rigid Flex/PTH Modeling					
DOW Materials					
LCP Materials					
UTC RP-46 Materials					
Single Ply Laminates					
Plasma Process Monitoring Equipment					
Low Profile copper Adhesion Work					
Dielectric Properties Test Method					
Moisture Absorption Test Methods					
Compositech Evaluation					
DiBlock Copolymers					
PTH Hole Model					
Process Development					
Other					

Surface Finishes Team

Adoption of Solderability Test Methods					
Increase Utilization of Imidazole at AT&T					
Reduced Solder Joint Rework					
DEC Liquid Soldermask Study					
TI Packaging/Aging Study					
Capillary Flow Design Adopted by HS					
Combined Development of Test Vehicles					
Alternate Surface Finishes					
Solder Wetting dynamics					
Surface Chemistry for Soldering					
Chemistry of Solders and Flukes					
Baseline/Benchmarking Studies					
Aging & Stressing					
Etching Studies					
Solderable Finishing Stressing					
OSP Development					
ROSA/PADS Monitoring					
Solder Joint Integrity/Attach Rel./					
Wire Bondability					
COB Passivation					
Process Development					
Other					

**NCMS/NIST PWB
Economic Impact Study**

Company Name

Est. Workyears Saved	Shortened Time to Practice	Productivity Improvement Increases	Testing Material and Machine Time Savings	Place an "X" if project would have started without this program	Money Saved
Yr.	Mo.	%	\$(K)	X	\$(K)

Imaging Team

Text & Evaluation Hardware					
Sharing of Test Methodology					
Photoresist Evaluations					
Etcher Evaluations					
New Innerlayer Line Approved					
Laser Imaging Evaluations					
Projection Imaging Evaluations					
Leap Frog Activities					
Process Development					
Other					

Product Team

Copper/Polymer Adhesion Work					
Nondestructive Test Development					
PTH Modeling Software					
Mag-Ion Process Development					
Redistribution Layer Development					
Benchmarking Using TekTrack					
Evolutionary Test Vehicle Design					
Evolutionary Test Vehicle Fabrication					
Evolutionary Test Vehicle Design – MOIT					
Revolutionary Test Vehicle Design Fabrication					
Develop Small Hole Drilling					
Small PTH Reliability Study					
Other					

Steering Group

QFD Information					
Advanced Technology Assessments					
BPA Type Information					
Leap Frog Activities					
Use of NCMS Library					
Program Final Report					
Quarterly Reviews					

Each question or statement below refers to the overall PWB Program, from the date it began to the present.

Technology Transfer

Number of papers presented related to the PWB Program

Professional meetings

Informal presentations to PWB supplier industry

Other (please explain)

TOTAL

Number of conferences attended in which you talked about
the PWB Program's activities

Percentage of the PWB supplier industry with which you
Interfaces with about the PWB Program

_____ %

Please describe your perceptions concerning the usefulness of these technology transfer efforts.
Anecdotes are welcome.

International Competitiveness Issues

Please respond to each statement and offer explanations for your opinions whenever relevant.

As a result of **my company's** involvement in the PWB Program, my company's share of each of the following segments of the world PWB market has (choose one response for each market segment – "increased," "stayed the same," "decreased," or "does not apply to my company.")

Market Segment¹

World Market Share Has

Automotive
Communications
Consumer Electronics
Computer and Business Equipment
Government and Military/Aerospace
Industrial Electronics
Instrumentation

I perceive that as a result of the accomplishments of the PWB Program, the **PWB industry's** share of the following segments of the world PWB market has (choose one response for each market segment – "increased," "stayed the same," or "decreased.")

Market Segment

World Market Share Has

Automotive
Communications
Consumer Electronics
Computer and Business Equipment
Government and Military/Aerospace
Industrial Electronics
Instrumentation

It is my impression that the international competitive position of the **semiconductor industry** has been affected by the accomplishments of the PWB Program in the following ways (please describe):

¹ These seven market segments were created by the IPC.

